Assimilation of Coastal Radar Surface Current Measurements in Shelf Circulation Models

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LONG-TERM GOALS

To understand the fundamental issues involved with data assimilation in the coastal ocean and to use this knowledge to develop optimal, nowcast and forecast systems.

OBJECTIVES

The immediate scientific objectives of this research project are to develop practical, but still nearly optimal, methods for the assimilation of surface current measurements from land-based radar systems in coastal circulation models and to apply these methods to measurements from the Oregon shelf.

APPROACH

An array of SeaSonde HF radars has been deployed along the Oregon coast by P. M. Kosro of the College of Oceanic and Atmospheric Sciences, OSU. Data from a two-site HF array, which provides measurements of surface currents over a region about 50 km square, have been collected since November 1997. This project is aimed initially at developing and applying, in cooperation with Kosro, methods for the assimilation of these measurements in coastal circulation models.

A long-term objective of this project is the development of a data assimilation method for surface currents based on the formulation of an optimal, weak constraint inverse model for the primitive equations with a turbulence submodel. The full primitive equations are sufficiently complicated that considerable difficulties exist with that task. Even basic questions about the nature of information contained in surface current data and its implications for the velocity and density distributions at depth are not easily addressed with the primitive equations.   For that reason, the data assimilation problem has been approached simultaneously from two directions; application of optimal variational inverse data assimilation schemes to simplified linear models and application of simplified, sub-optimal data assimilation schemes to a full primitive equation model.

Studies using a linear stratified model have been undertaken by the P.I.'s together with G. D. Egbert, R. K. Scott and A. Kurapov to provide an improved understanding of mathematical and physical issues associated with assimilation of surface current measurements. The present linear stratified model includes the effects of surface and bottom Ekman layers, and has been widely used in previous theoretical studies of shelf circulation (e.g., Clarke and   Brink, 1985). Although this model clearly has limitations, it includes representations of the essential physical effects of stratification, surface and

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bottom frictional processes, and shelf bottom topography. The use of linear models also allows a systematic examination of the sensitivity of errors in the assimilation output products to errors in surface velocity measurements, wind stress, heat fluxes, initial conditions and boundary conditions.

At the same time, as part of closely related research in the OSU NOPP project ``The Prediction of Wind-Driven Coastal Circulation'', the P.I.'s have been working with G. Egbert, P. Oke and P. M. Kosro on the development of a practical, sub-optimal assimilation scheme for implementation with the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) and on the application of this scheme to HF radar measurements off the Oregon coast. A data assimilation system that employs the mathematical framework of the Physical Space Analysis System (PSAS), utilized by the NASA Data Assimilation Office (Cohn et al., 1998), has been developed for use in POM.

WORK COMPLETED

A study involving application of an optimal variational inverse scheme for assimilation of surface data in an idealized linear stratified coastal model has been completed and is reported in Scott et al. (1999). The forward model involves use of a simplified flat bottom geometry and represents effects of vertical diffusion through vanishingly thin surface and bottom Ekman layers (Allen, 1973).   Consideration is restricted to the response of two-dimensional flows (variations across-shore and with depth, uniformity alongshore) forced by wind stress at a single frequency . The use of this idealized model allows significant analytical progress. The inverse model comprises the forward model and a set of adjoint equations, the solution of which minimizes a penalty functional of data and model errors to provide a weighted least squares fit to the forward model and to the data. Strong and weak constraint formulations of the inverse model have been investigated. In the strong constraint formulation, the only source of model error is in the open ocean boundary condition. In the weak constraint, there are sources of model error in both the open ocean boundary and the model equations themselves.

Analytic expressions for the inverse solutions have been obtained in both the strong and the weak constraint formulations in terms of a sum of representer functions, over the data array. There is a representer function associated with each observation in space and time. The representer function for a given observation contains information about the impact of assimilating the result of that particular observation into the analysis for a given model and given cost function. Twin experiments have been investigated in which data were sampled from a known ocean state, derived from a solution to the forward model, to assess how well the inverse method can recreate the original ocean state. The dependence of the inverse solution on the data error variance has been shown explicitly. Further, a measure of the total error of the inverse solution from the known ocean state has been used to determine which model weights provide the best inverse solution.

Work with this linear stratified model has been extended to consider general time-dependent, three-dimensional flows, while still retaining idealized coastal geometry (Kurapov, et al., 1999). Although this model is simplified, it contains a representation of the coastal-trapped wave dynamics that will be an important physical component of full primitive equation models with realistic topography. A generalized inverse has been developed and again progress with finding analytical solutions has been possible. In applications of coastal circulation models, it is typical that there are considerable uncertainties in initial conditions and in open boundary conditions at across-shelf boundaries. The generalized inverse formulation here has been used specifically to investigate the effectiveness of surface data in restoring the state of the system at the initial time and at the open boundary.

For the studies utilizing POM, the model is applied to a limited-area high resolution coastal domain for the central Oregon coast (Oke et al., 1999). Realistic bottom topography for the Oregon continental shelf and slope is embedded in a large scale periodic channel. This geometry provides a useful domain for well-posed numerical experiments involving wind-driven upwelling circulation on the Oregon shelf. A series of model-data comparisons for summer 1998 indicates that the model is capable of reproducing a substantial fraction of the surface and sub-surface variance in the shelf velocity field. The model has been forced with observed winds from 17 different "typical" summers (July and August) between 1969 and 1998. From the results of these experiments, time- and ensemble-averaged mean fields and covariance functions relevant to assimilation of surface current measurements at sub-inertial frequencies have been calculated. These functions have been used to calculate an approximate non-isotropic, non-homogeneous forecast error covariance matrix for the PSAS scheme. A time-distributed, sequential assimilation procedure, that specifically addresses issues concerning primitive equation initialization and assimilation of low-pass filtered data (that removes tides and inertial period oscillations) has been developed for use with the PSAS scheme. The effectiveness of this assimilation procedure has been evaluated with a series of twin experiments.

RESULTS

For the two-dimensional linear model study reported in Scott et al. (1999), the assimilation scheme uses an inverse formulation to find the best fit to the model, to the coastal boundary condition, which represents our knowledge of the open ocean, and to the data. Without this inverse formulation, simply replacing the coastal boundary condition with an extra surface boundary condition consisting of the data results in an ill-posed problem. The inverse formulation illustrates explicitly how the ill-posedness is resolved: through the regularization of an ill-conditioned linear operator, whose inverse is a linear transformation from the data to the solution at depth.

The inverse solution is constructed as a linear combination of representer functions. The representer functions provide important information about the domain of influence of each data point, about optimal location and resolution of the data points, about the error statistics of the inverse solution itself and about how that depends upon the error statistics of the data and of the model. Twin experiments illustrate how a well known ocean state can be reconstructed from sampled data. Consideration of the statistics of an ensemble of such twin experiments provides insight into the dependence of the inverse solution on the choice of weights, on the data error, and on the sampling resolution.

For the three-dimensional, fully time-dependent linear problem (Kurapov et al., 1999), the representer functions show interesting physical features concerning the zone of influence of each surface data point. The representer associated with uncertainty in the governing equation has a significant propagating component (Figure 1) associated with the coastal-trapped wave dynamics present in the model. This clearly illustrates the non-local nature, in both time and alongshore coordinate, of surface data influence. Results from twin experiments give an explicit demonstration of the effectiveness of the inverse solution in restoring unknown initial conditions and across-shelf boundary conditions.

For the studies utilizing POM (Oke et al., 1999), the capability of a shelf circulation model to represent important features of the observed shelf surface and subsurface velocity field has been shown (Figure 2). The effectiveness of a practical data assimilation scheme based on PSAS, but structured to address
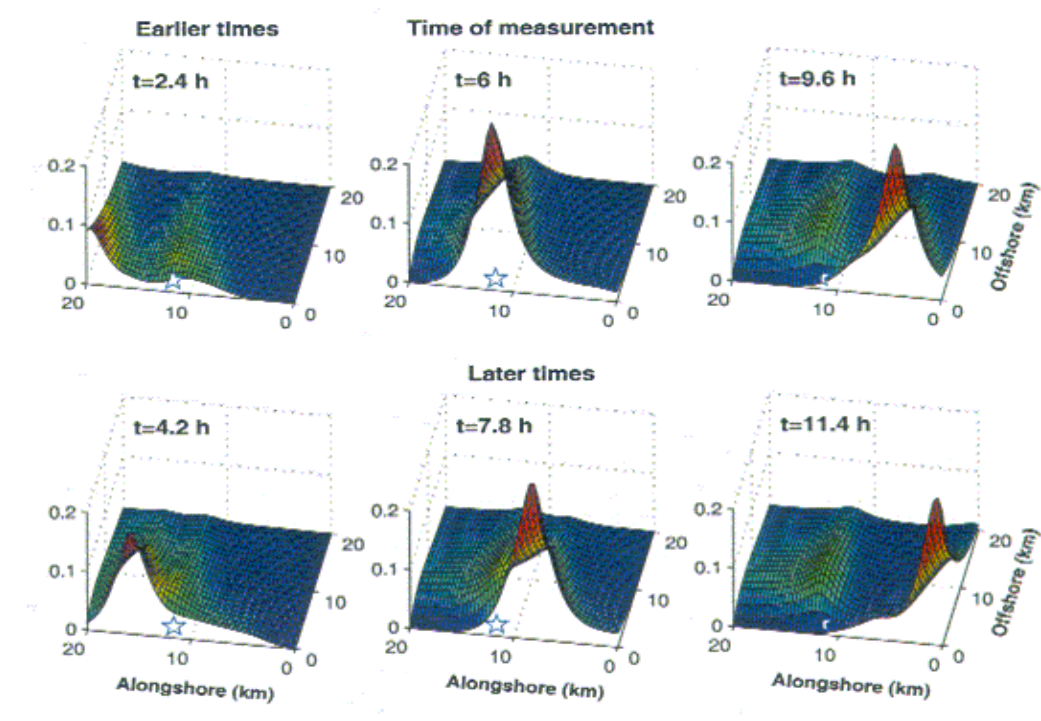
1. Time-development of the representer function at the sea surface. The representer shows the zone of influence of the datum in space and time. The surface datum is from a measurement at x = 2 km, y = 12 km, and t = 4.2 h, where (x,y) are across-and along-shore coordinates, respectively. The star denotes the spatial location of the datum.

issues of primitive equation initialization and filtered data assimilation, has been demonstrated through a series of identical twin experiments.

IMPACT/APPLICATIONS

The studies with variational inverse schemes applied to linear models have begun to answer some of the basic questions associated with the assimilation of surface current measurements in coastal circulation models. In particular, these questions concern the extent of surface data influence on the flow at depth, the capability to retrieve unknown initial and boundary conditions, and the dependence of the inverse solution on assumed model and data error weights. The studies with POM have produced promising results regarding assimilation of coastal radar surface current measurements in a full primitive equation model utilizing a practical data assimilation scheme.

TRANSITIONS

RELATED PROJECTS

Some aspects of these data assimilation studies are jointly funded by ONR Grant N00014-98-1-0787 (NOPP) "The Prediction of Wind-Driven Coastal Circulation".
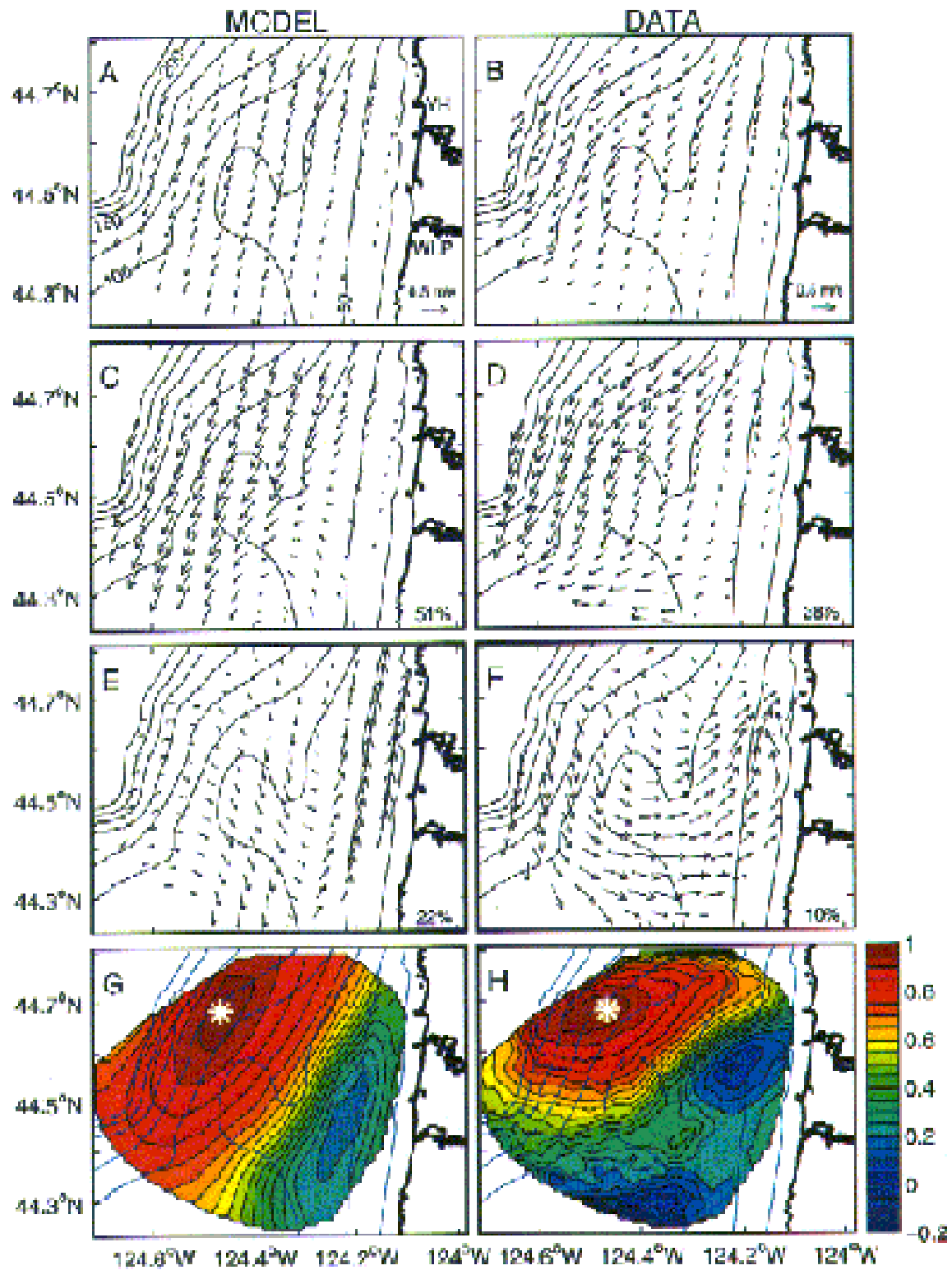
2. *Statistical comparisons between the modeled (left) and observed (right) surface velocity fields for the summer of 1998 showing; the mean vector fields (A-B); the dominant empirical orthogonal functions (C-F, % variance is indicated in the bottom right of each panel); the cross-correlations of the along-shore velocities at a fixed point (*) and elsewhere in the CODAR region (G-H).*

REFERENCES

Allen, J. S., 1973. Upwelling and coastal jets in a continuously stratified ocean. *Journal of Physical Oceanography,* **3**, 245-257.

Blumberg, A. F., and G. L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model, in *Three-dimensional Coastal Ocean Models*, Coastal Estuarine Sci. Ser., Vol. 4, edited by N. Heaps, pp. 1-16, A.G.U., Washington D.C.

Clarke, A. J., and K. H. Brink, 1985: The response of stratified, frictional flow of shelf and slope waters to fluctuating large-scale, low-frequency wind forcing, *J. Phys. Oceanogr*., **15**, 439-453.

Cohn, S. E., A. da Silva, J. Guo, M. Sienkiewicz, and D. Lamich, 1998: Assessing the Effects of Data Selection with the DAO Physical-Space Statistical Analysis System. *Mon. Wea. Rev*., **126**, 2913-2926.

Kurapov, A. L., J. S. Allen, R. N. Miller, and G. D. Egbert, 1999: Generalized inverse for baroclinic coastal flows. Preprints*, Third Conference on Coastal Atmosphere and Oceanic Prediction and Processes*. New Orleans, LA. Amer. Meteor. Soc.

Oke, P. R., R. N. Miller, J. S. Allen, G. D. Egbert, and P.M. Kosro, 1999: Assimilation of surface velocity data into a coastal ocean model. Preprints*, Third Conference on Coastal Atmosphere and Oceanic Prediction and Processes*. New Orleans, LA. Amer. Meteor. Soc.

Scott, R. K., J. S. Allen, G. D. Egbert, and R. N. Miller, 1999: Assimilation of surface current measurements in a coastal ocean model, submitted to *J. Phys. Oceanogr*.